Journal of Non-Crystalline Solids 358 (2012) 2295–2298

Contents lists available at SciVerse ScienceDirect

Journal of Non-Crystalline Solids

journal homepage: www.elsevier.com/locate/jnoncrysol

Design and application of dielectric distributed Bragg back reflector in thin-film silicon solar cells

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ARTICLE INFO

Article history:
Received 13 August 2011
Received in revised form 30 October 2011
Available online 1 December 2011

Keywords:
Distributed Bragg reflector;
Photonic crystals;
Transparent conductive oxide;
Thin-film silicon solar cells

ABSTRACT

A dielectric distributed Bragg reflector (DBR) formed by four pairs of hydrogenated amorphous silicon/silicon nitride layers is used as the back reflector in thin-film silicon solar cells. The DBR was designed to perform in a broad wavelength range with the peak reflectance at 600 nm. The DBR was fabricated at low substrate temperature (172 °C) and applied at the rear side of flat and textured amorphous silicon single-junction solar cells in both superstrate (*pin*) and substrate (*nip*) configurations. The spectral response and electrical I–V characteristics were measured. Solar cells with optimized DBR exhibit an enhanced external quantum efficiency in the long wavelength range and the electrical performance is comparable to solar cells having conventional Ag back reflector.

1. Introduction

Thin-film silicon solar cells (TFSSC) are attractive photovoltaic (PV) devices because of the lower processing temperature and material consumption with respect to other PV technologies. Light management techniques are applied to TFSSC in order to increase the short-circuit current density and thus the conversion efficiency [1]. Light trapping techniques in particular aim to confine the light in the absorber layer. The simultaneous combination of surface-textured substrates for light scattering at the front side and back reflectors for high reflectance at the rear side is the standard light trapping approach in TFSSC. However, the back reflectors which are textured and usually metallic, serving also as electrical contacts, suffer from unwanted plasmon absorption [2]. An alternative approach is the wavelength-selective reflection at the rear side of TFSSC using dielectric one-dimensional (1-D) photonic crystals (PCs) in the role of distributed Bragg reflector (DBR) [3,4]. Dielectric 1-D PCs are multilayer structures in which two layers (a pair) with different optical properties are periodically alternated. High reflectance (close to 100%) can be achieved in a broad wavelength range centered around the design wavelength called the Bragg wavelength (λ_B). A combination of thick transparent conductive oxide (TCO) and dielectric DBR can serve at the same time as the back reflector and the electrical contact in a TFSSC while avoiding unwanted optical losses.

In this paper we present the design and application of the dielectric DBR in flat and textured single-junction TFSSC in both superstrate (*pin*) and substrate (*nip*) configurations. After choosing the materials for the back reflector (TCO and DBR), different combinations of λ_B and number of pairs were investigated in optical simulations in order to achieve the highest short-circuit current density (J_{SC}). Afterwards, *pin* and *nip* TFSSC with the dielectric DBR were fabricated on both flat and textured substrates. In the case of the *pin* configuration two photolithographic methods were developed in order to precisely define the contact area. Spectral response and current–voltage (I–V) characteristics of the fabricated devices were measured. We present the influence of the back contact design on the electrical properties of TFSSC and demonstrate the feasibility of using the TCO-DBR stack as the back contact/reflector.

2. Experimental

2.1. Optical simulations

An optimal dielectric DBR for single-junction a-Si:H solar cells was designed using the Advanced Semiconductor Analysis (ASA) software [5]. Hydrogenated amorphous silicon and silicon nitride (a-Si:H/a-SiN$_x$:H) films were used for the alternating pairs. Simulations of flat solar cells with the rear contact/reflector formed by the back ZnO:Al (BAZO) and 1-D PC were carried out. In the simulations the number of pairs of the DBR (from 1 to 10) and the λ_B (from 500 nm to 800 nm) were varied. The 1-D PC structure was tested in two arrangements: (i) a-Si:H or (ii) a-SiN$_x$:H as the first layer on the BAZO layer. The absorptance in the *i*-layer was used to calculate the short-circuit current density (J_{SC}) in the wavelength range from 300 nm to 850 nm. Solar cells with metal Ag and Al back reflectors were also simulated. Through a comparison of the simulated J_{SC} the optimal DBR was selected. The simulated TFSSC structures are reported in Table 1. The thickness of the BAZO layer is a

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doi:10.1016/j.jnoncrysol.2011.11.025

Table 1
Simulated TFSSC structures using the ASA software. ITO indicates Indium-Tin-Oxide.

Structure	*pin*	*nip*
Substrate	Glass (0.6 mm)	–
Front TCO	ITO (400 nm)	ITO (80 nm)
p	a-SiC:H (15 nm)	
i	a-Si:H (300 nm)	
n	a-Si:H (20 nm)	
Back TCO	AZO (500 nm)	
Back reflector	1-D PC or Ag (300 nm) or Al (300 nm)	

compromise between sufficient conductivity and transparency, while the thickness of the individual layers in the 1-D PC is calculated on a quarter-wavelength basis for each simulated λ_B [3].

Using the optimal DBR we calculated the internal reflectance at the n-layer/BAZO interface for Ag, Al, and 1-D PC back reflectors and the reflectance at the air/1-D PC interface for glass and Ag substrates to verify the experimental results obtained at the device level.

2.2. Samples fabrication

Glass substrates were used for flat devices, while SnO_2:F (FTO) on glass (Asahi-U type TCO) was deployed as a textured counterpart (front TCO in the *pin* configuration, textured substrate in the *nip* configuration). ITO and BAZO films were deposited using radio frequency (RF) magnetron sputtering while physical vapor deposition (PVD) was used for the Ag and Al films. The *p-i-n* junctions and the optimal DBR were fabricated at 180 °C and 172 °C, respectively, using RF plasma-enhanced chemical vapor deposition (RF PECVD). The optimal DBR was also deposited on glass and glass/Ag substrates for reflectance measurements. Solar cells in the *pin* configuration were tested with three different back reflectors (optimal 1-D PC, Ag, and Al) that were applied at the rear side of the BAZO layer. In the *nip* configuration Al was not used.

For the *pin* devices with dielectric DBRs two different methods were developed to precisely define the back contact area (see Fig. 1). In both methods, dots displaced (DD) and vertical vias (VV), a reactive ion etching (RIE) step consisting of 10 min of plasma etching from a CF_4-SF_6-O_2 gaseous mixture was used to define the individual 1-D PC pads. The BAZO layers were wet-etched in a 0.5% HCl solution. Back metal (Ag) pads were evaporated only to improve the electrical contact between the BAZO layers and measurement probes. For the *nip* solar cells the front ITO deposited through a mask defines the device contact area.

2.3. Samples characterization

The complex refractive indices of the simulated materials were characterized using a Perkin-Elmer 950 spectrophotometer equipped with the ARTA accessory [6] and applying the variable angle spectrometry technique [7]. The spectrophotometer with the integrating sphere was used to measure the reflectance of the optimal 1-D PC in air deposited either on glass or on Ag-coated glass. A four-probe setup was used to measure the sheet resistance (R_S) of the TCOs. The ITO films exhibited $R_S < 10\ \Omega/\square$ and the BAZO films had $R_S \sim 20\ \Omega/\square$. In both *pin* and *nip* devices the BAZO films were the only electrical contact at the rear side when combined with the DBR. The thicknesses of all layers presented in Table 1 were confirmed with

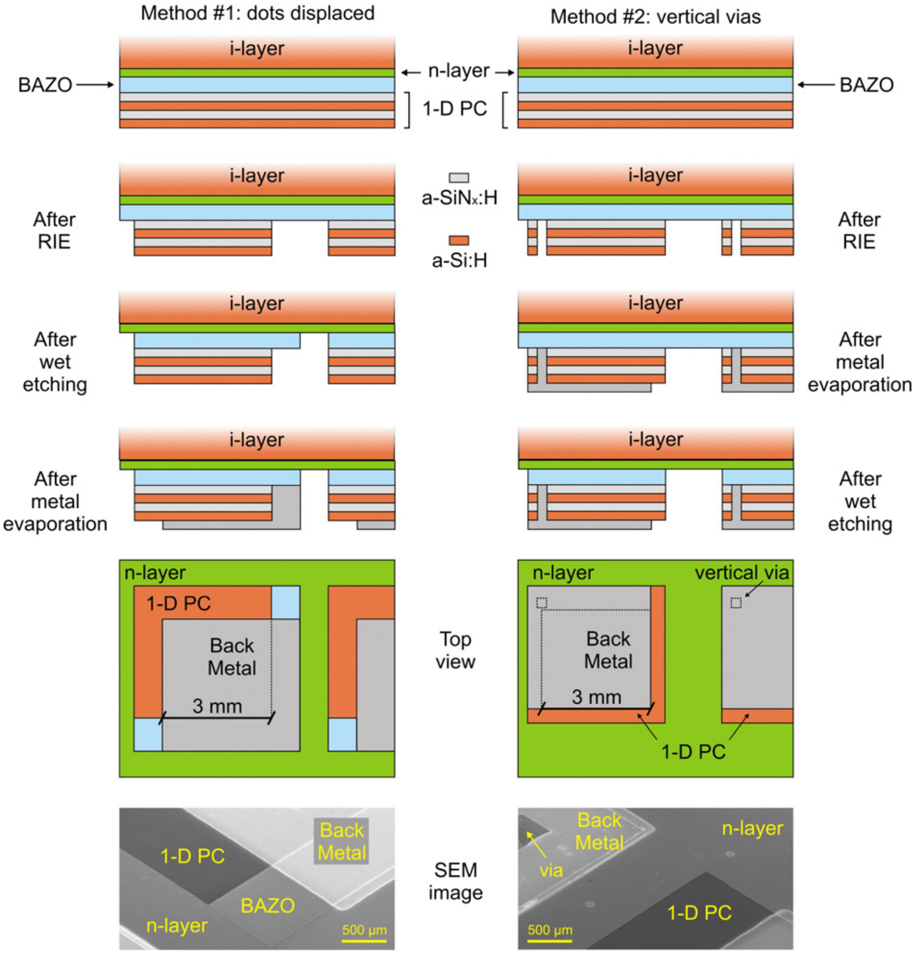

Fig. 1. Flow charts for fabricating the two different back contacts for flat and textured *pin* cells with dielectric DBR.